# Initial state & pre-equilibrium effects in p+A collisions

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*Based on work in collaboration with Schenke, Venugopalan, Lappi*

INT Workshop, Seattle July 2015

BROOKHAVEN NATIONAL LABORATORY

# Outline

- Introduction & Motivation
- Initial state and early time dynamics in p+A

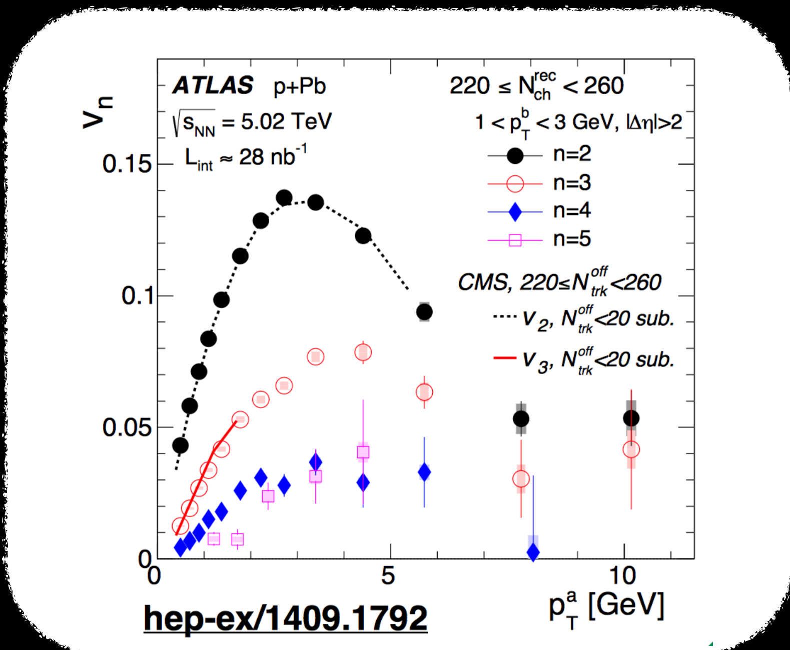
  — Azimuthal anisotropies from initial state & early time effects

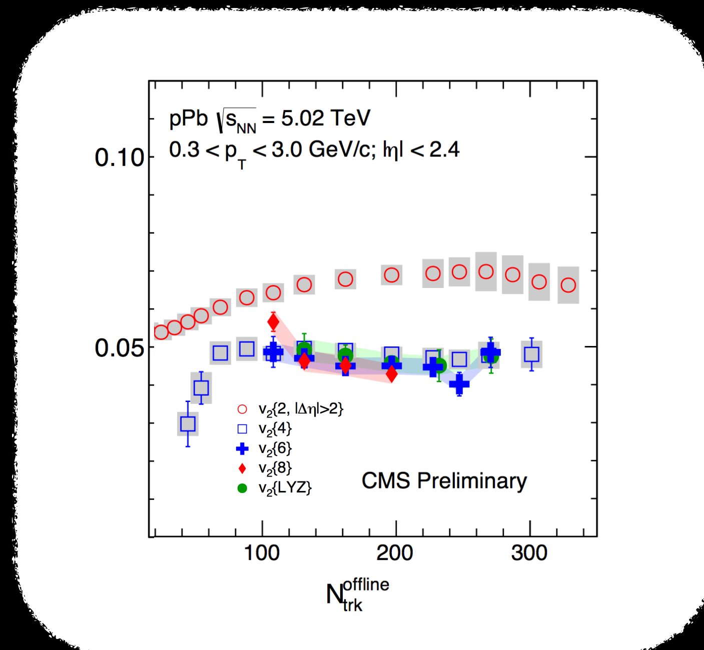
- Event geometry in p+A collisions & Nucleon structure at high-energies

  — Event-by-event fluctuations of proton ‘shape’ & importance for hydrodynamic calculations

# p+A collisions

- High multiplicity p+A collisions reveal pronounced azimuthal correlations; qualitative features reminiscent of A+A




- Correlation extends up to high $p_T \sim 10$GeV
- Correlation between many particles (>8) observed

-> Event-by-event particle production appears to be anisotropic — Spontaneous breaking of rotational symmetry

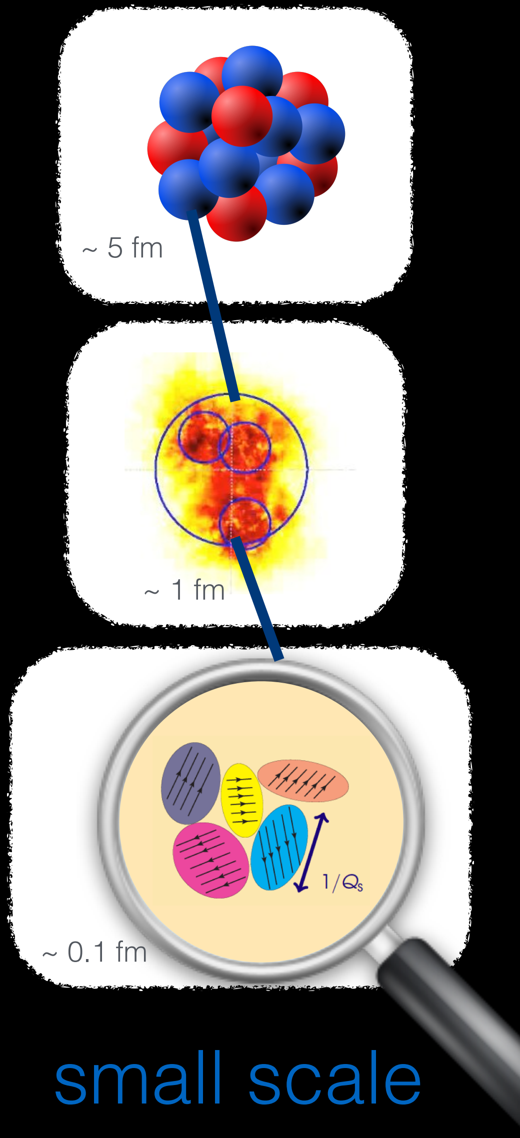
# General picture of a high-energy collision

- High-energy scattering of projectile and target is almost instantaneous.
- Semi-classical picture: In each event the projectile resolves a particular realization (snapshot) of the target wave-function.
- Convenient variables to describe nucleon structure are the light-like Wilson lines

$$V_x = \mathcal{P}\, e^{-ig\int dx^- A^+}$$

(corresponds to forward scattering amplitude of a parton in eikonal approximation)

large scale




small scale

# Origin of correlations

- Color-electric fields inside the nucleus

$$E_i(\mathbf{x}_T) = \frac{i}{g} V(\mathbf{x}_T) \partial_i V^\dagger(\mathbf{x}_T)$$

fluctuate from event to event, and are locally organized in domains of size ~1/Qs.

- When a parton scatters off a domain receives a kick in the direction of the chromo-electric field.

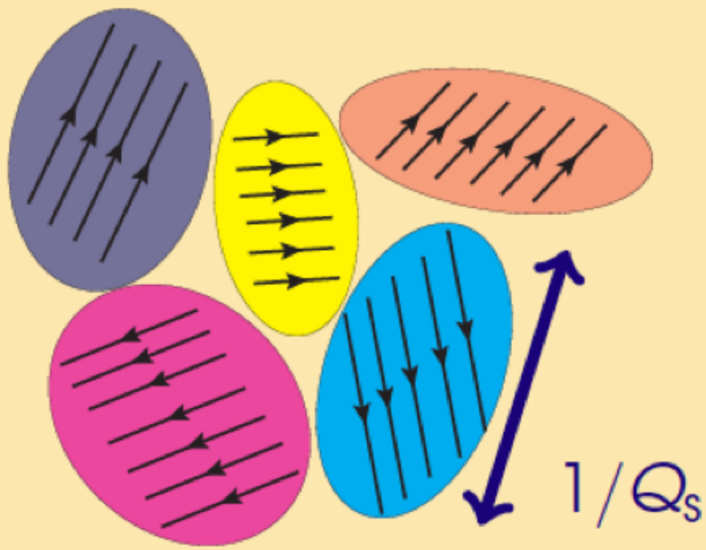



Fig. by T. Lappi

When two (or more) partons scatter off the same domain and are in the same color state, they will receive a similar kick

-> Generally leads to a correlation which is $\sim 1/N_c^2$ and $\sim 1/Q_s^2 S_T$

# q/g+A collisions

- Description in the dilute-dense framework as scattering of a quark/gluon wave-packet off a high-energy proton target

$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_T} \right\rangle = \int_{\mathbf{p}_T,\mathbf{b}_T,\mathbf{r}_T} W_{q/g}(\mathbf{p}_T,\mathbf{b}_T)\; e^{-i(\mathbf{k}_T-\mathbf{p}_T)\mathbf{r}_T}\;\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_T+\mathbf{r}_T/2)V^\dagger(\mathbf{b}_T-\mathbf{r}_T/2)\right\rangle$$

Single-inclusive distribution

Incoming q/g wave-packet

Quark/Gluon elastic scattering matrix

- Can be turned into a model for (forward) p+p/A by considering UPD for Wigner function and convolution with fragmentation function (Blaizot,Gelis,Venugopalan; Dumitru,Jalilian-Marian,…)

# q/g+A collisions

- While event-by-event the spectrum is azimuthally anisotropic, the event average of single inclusive spectrum is of course isotropic

$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_T} \right\rangle = \int_{\mathbf{p}_T,\mathbf{b}_T,\mathbf{r}_T} W_{q/g}(\mathbf{p}_T,\mathbf{b}_T)\; e^{-i(\mathbf{k}_T-\mathbf{p}_T)\mathbf{r}_T}\; \left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_T+\mathbf{r}_T/2)V^\dagger(\mathbf{b}_T-\mathbf{r}_T/2)\right\rangle$$

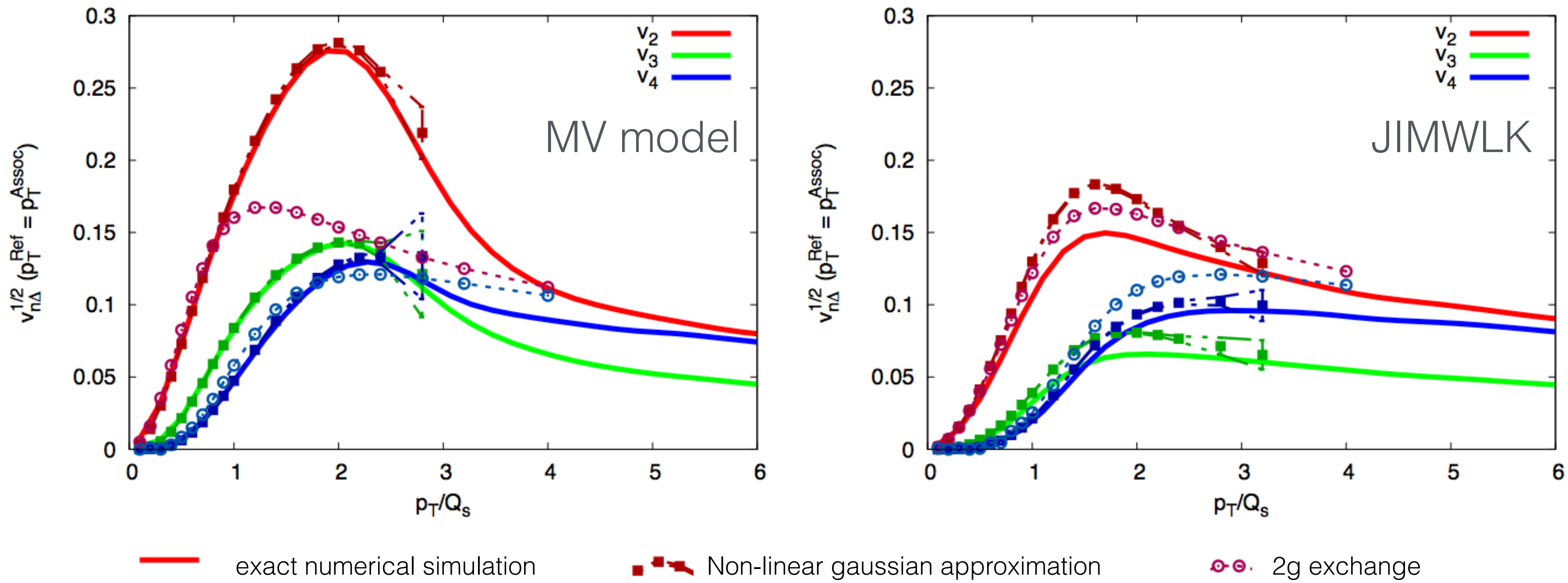
- However, the event-by-event fluctuations manifest themselves in multi-particle spectrum

$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_1 d^2\mathbf{k}_2} \right\rangle = \int_{\mathbf{p}_1,\mathbf{b}_1,\mathbf{r}_1}^{\mathbf{p}_2,\mathbf{b}_2,\mathbf{r}_2} W_{q/g}(\mathbf{p}_1,\mathbf{b}_1)\; e^{-i(\mathbf{k}_1-\mathbf{p}_1)\mathbf{r}_1}\; W_{q/g}(\mathbf{p}_2,\mathbf{b}_2)\; e^{-i(\mathbf{k}_2-\mathbf{p}_2)\mathbf{r}_2}$$
$$\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_1+\mathbf{r}_1/2)V^\dagger(\mathbf{b}_1-\mathbf{r}_1/2)\mathrm{tr}_{f/a} V(\mathbf{b}_2+\mathbf{r}_2/2)V^\dagger(\mathbf{b}_2-\mathbf{r}_2/2)\right\rangle$$

and give rise to (long range) azimuthal correlations.

# q/g+A collisions

Azimuthal correlations in q+A scattering

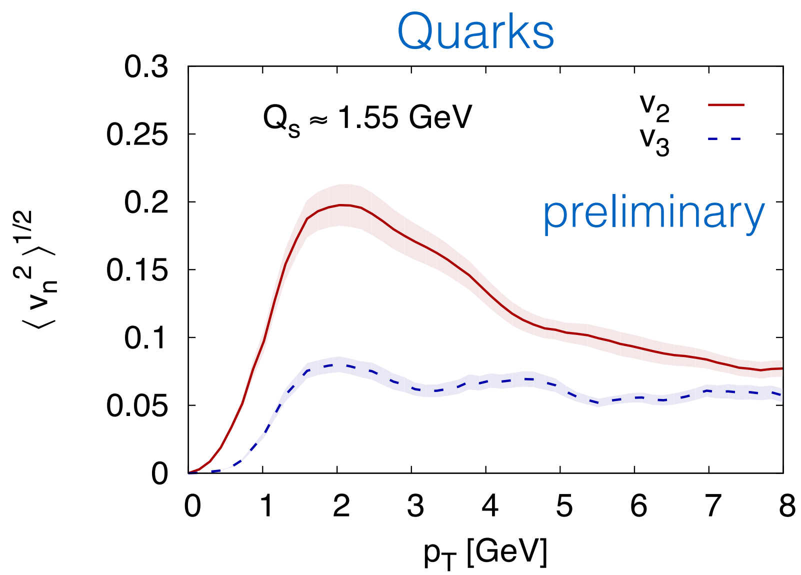



(Lappi,SS, Schenke, Venugopalan in preparation)

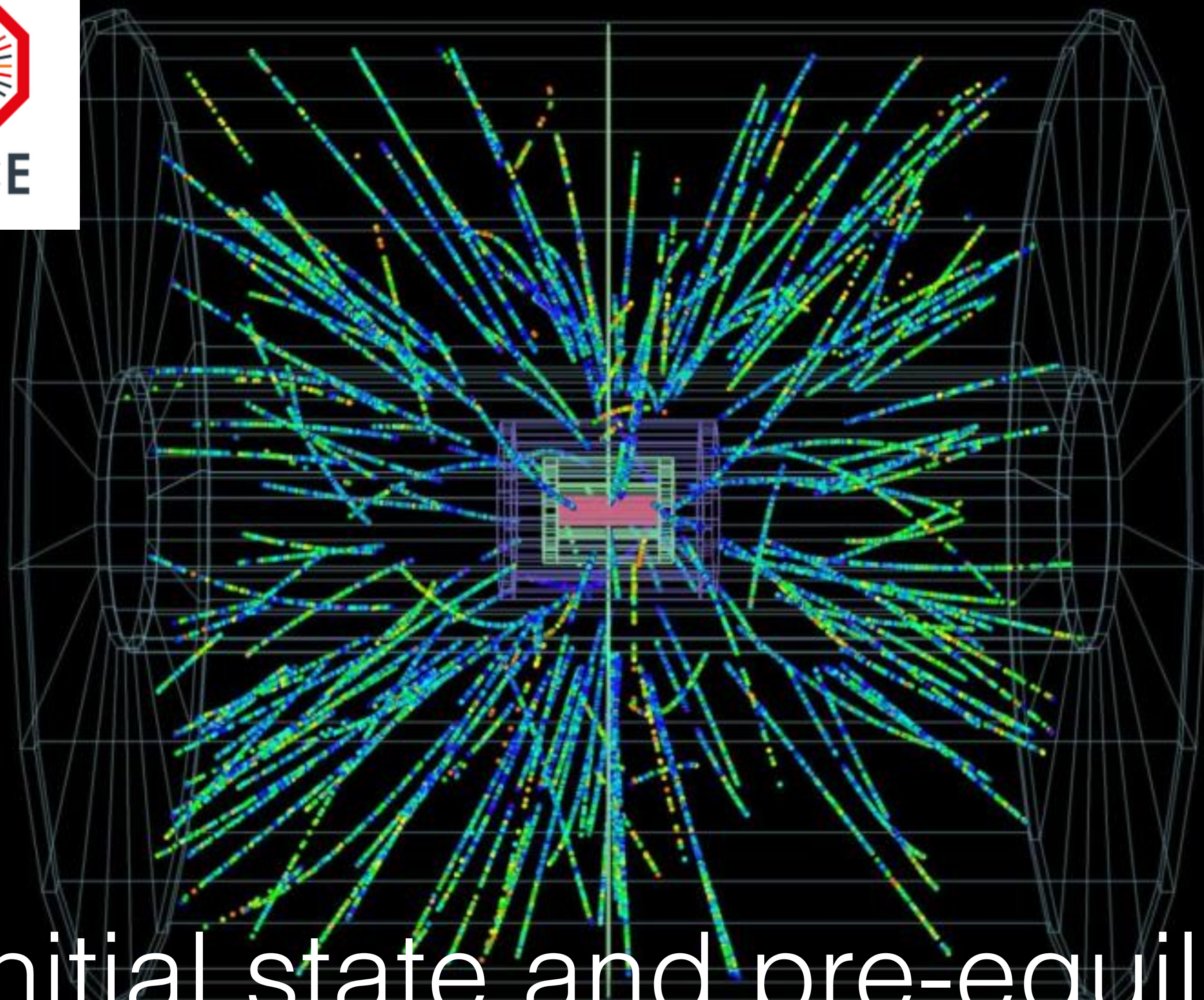
-> Sizeable $v_n$'s up to high $p_T$ — Qualitative agreement between different models

# q/g+A collisions

Qualitative comparison of quarks and gluons




-> No odd harmonics generated for gluons through purely initial state effects. Same if q/qbar combined.

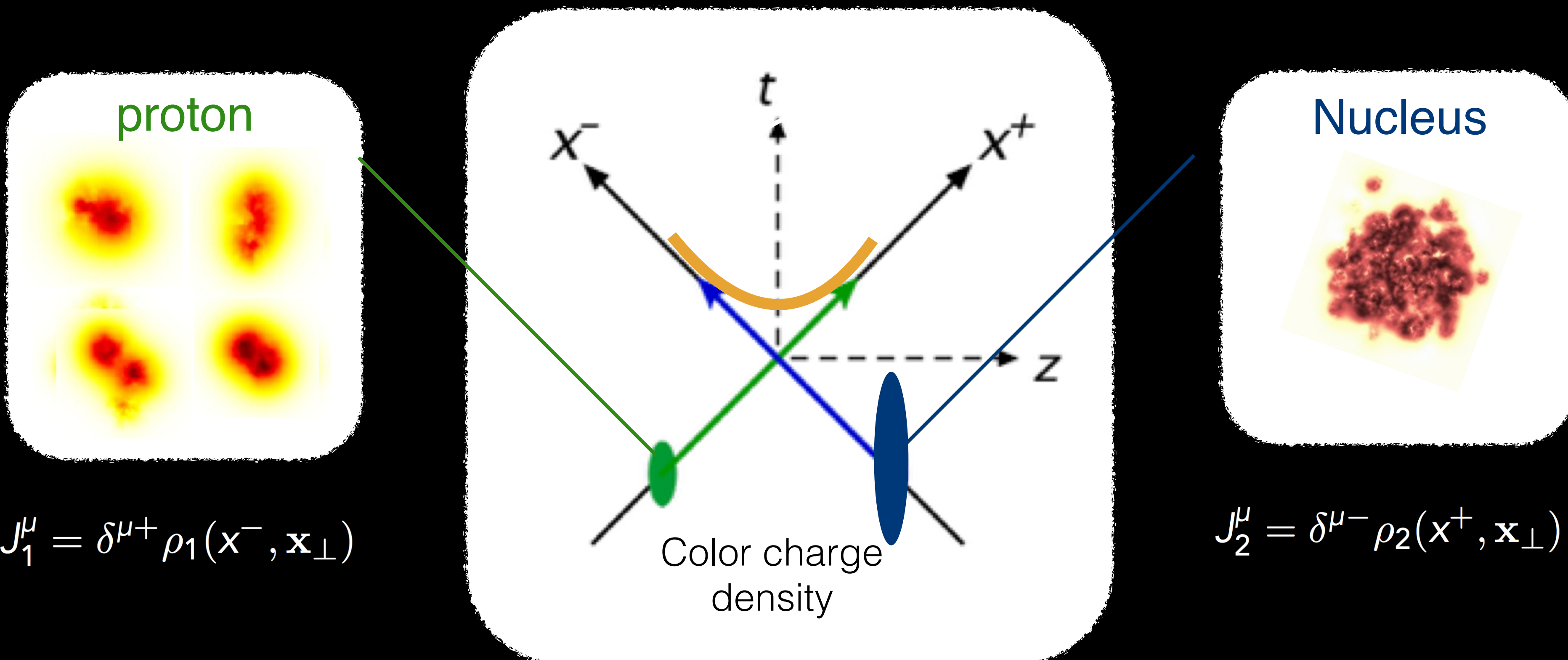


# Initial state and pre-equilibrium effects in p+A collisions

# p+A collisions

High multiplicity events require that both proton and nucleus are treated as dense objects with high gluon density.

-> Description of initial state and early-time dynamics in the color-glass condensate framework




$J_1^\mu = \delta^{\mu +} \rho_1(x^-, \mathbf{x}_\perp)$

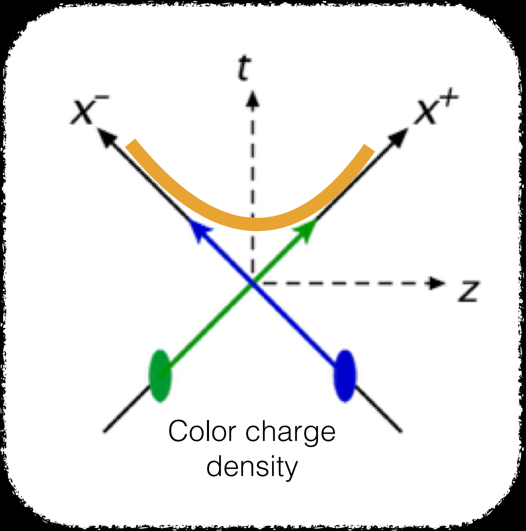
$J_2^\mu = \delta^{\mu -} \rho_2(x^+, \mathbf{x}_\perp)$

-> Study correlations in gluon production at mid-rapidity

# p+A collision

Initial state (τ=0+) and early time dynamics described by the solution of classical Yang-Mills equations to leading order in $\alpha_s$ (Kovner,McLerran,Weigert,Krasnitz, Venugopalan,Lappi …)

$$[D_\mu, F^{\mu\nu}] = J^\nu$$



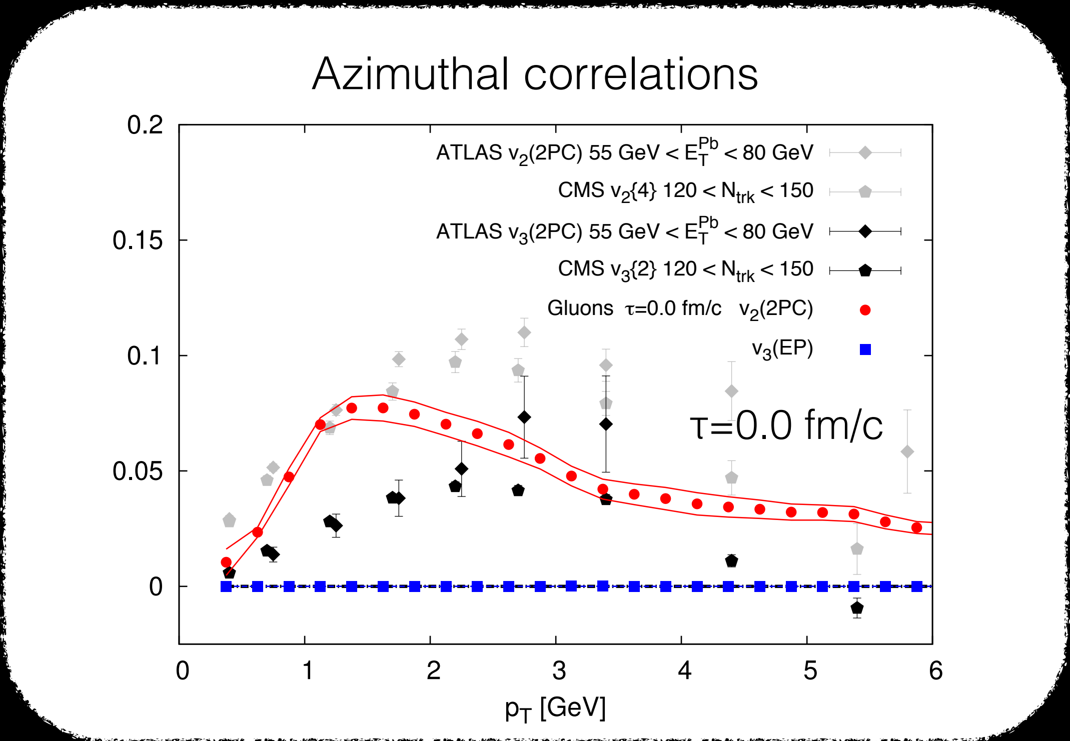

Solved numerically using lattice gauge theory techniques to study initial state and early time dynamics.

Measure gluon spectrum at different times of the CYM evolution and extract Fourier harmonics $v_n(p_T)$ from event plane and 2PC technique

Includes initial state contribution to $v_n$ as well as effects coherent final state interactions at $\tau>0$

# Initial state in p+A

- Initial state properties immediately after the collision ($\tau=0^+$)

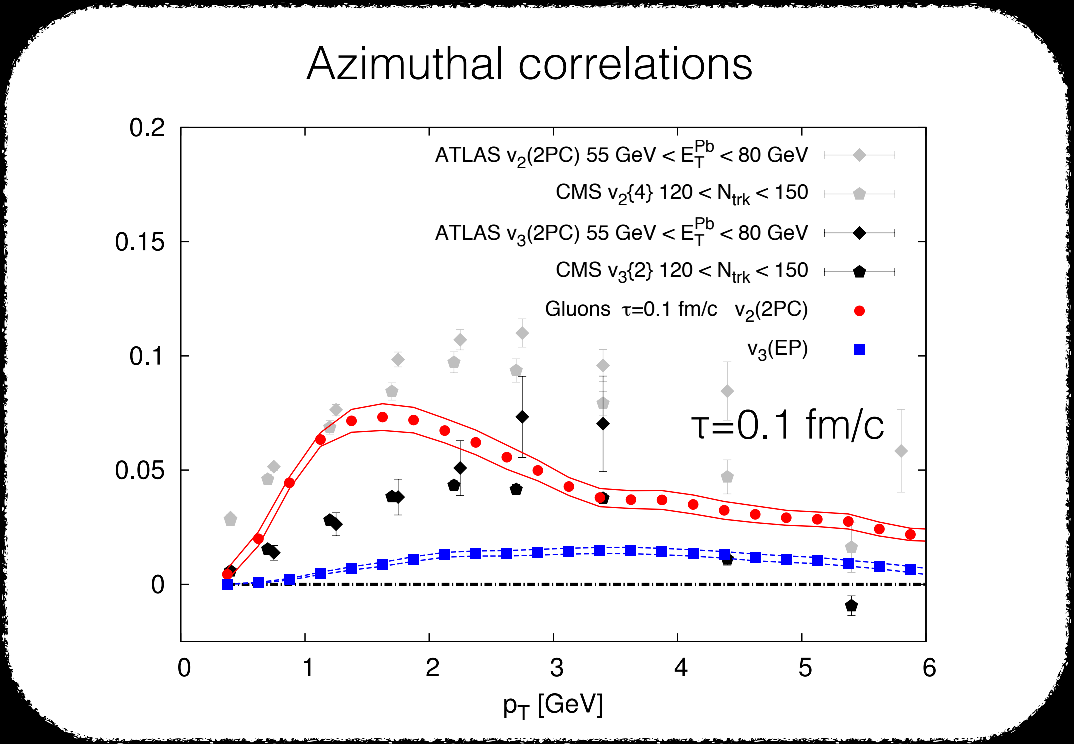



-> Significant momentum space anisotropy $v_2$ at $\tau=0$ due to production mechanism.

-> No odd harmonics for gluons without final-state interactions. Initial spectrum symmetric under $\mathbf{k}_T$<->-$\mathbf{k}_T$

# Dynamics in p+A collisions

- Classical (2+1D)Yang-Mills evolution after the collision — includes re-scattering of produced gluons




(SS, Schenke, Venugopalan arXiv:1502.01331)

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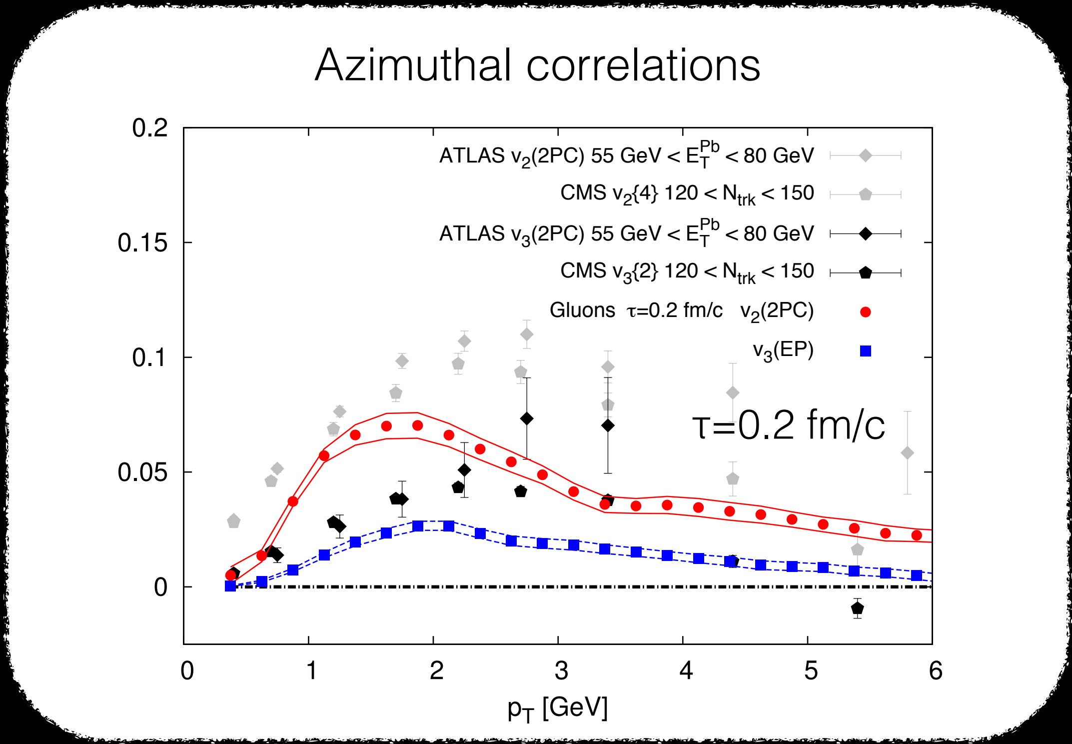


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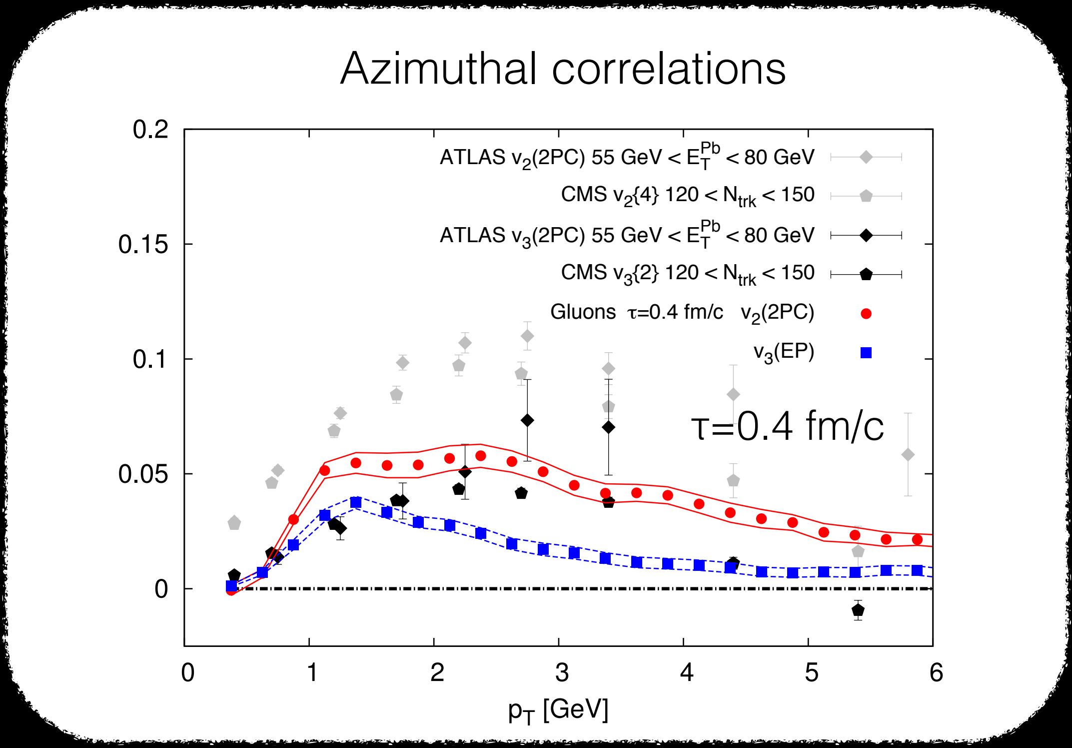
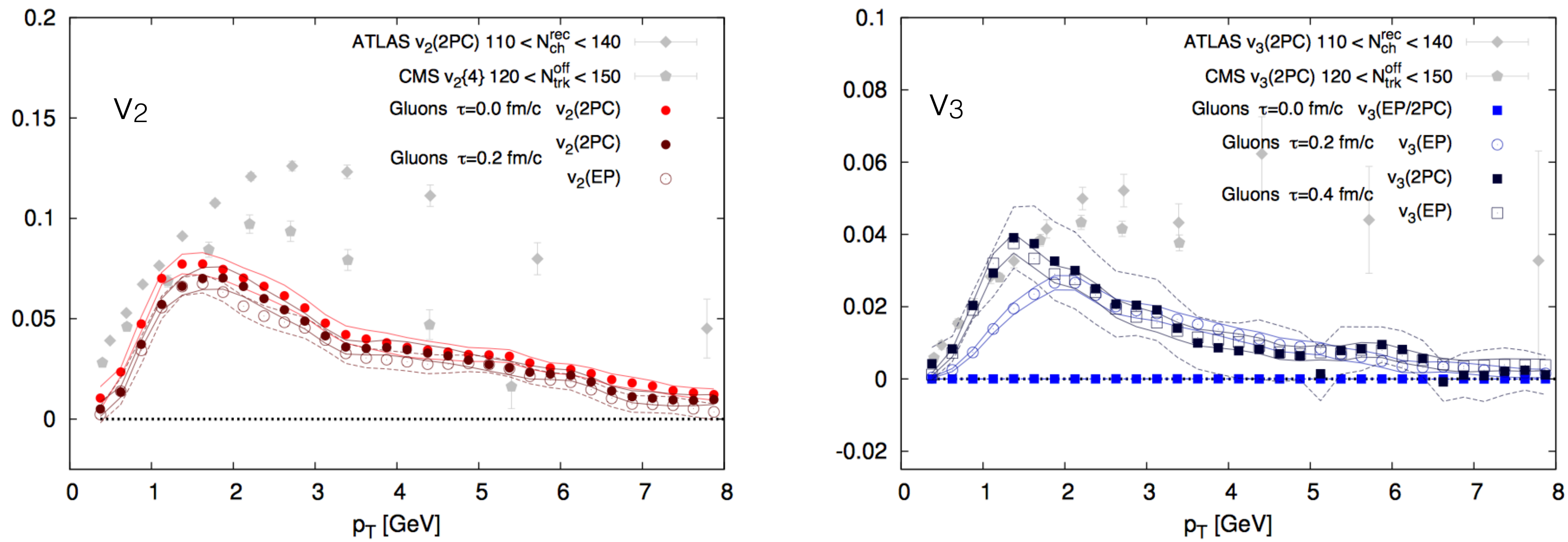



(SS, Schenke, Venugopalan arXiv:1502.01331)

-> Sizeable odd harmonics for gluons generated by pre-equilibrium dynamics on a time scale < l fm/c

# Effect of CYM evolution

Evolution of $v_2$ and $v_3$ in central p+Pb collision

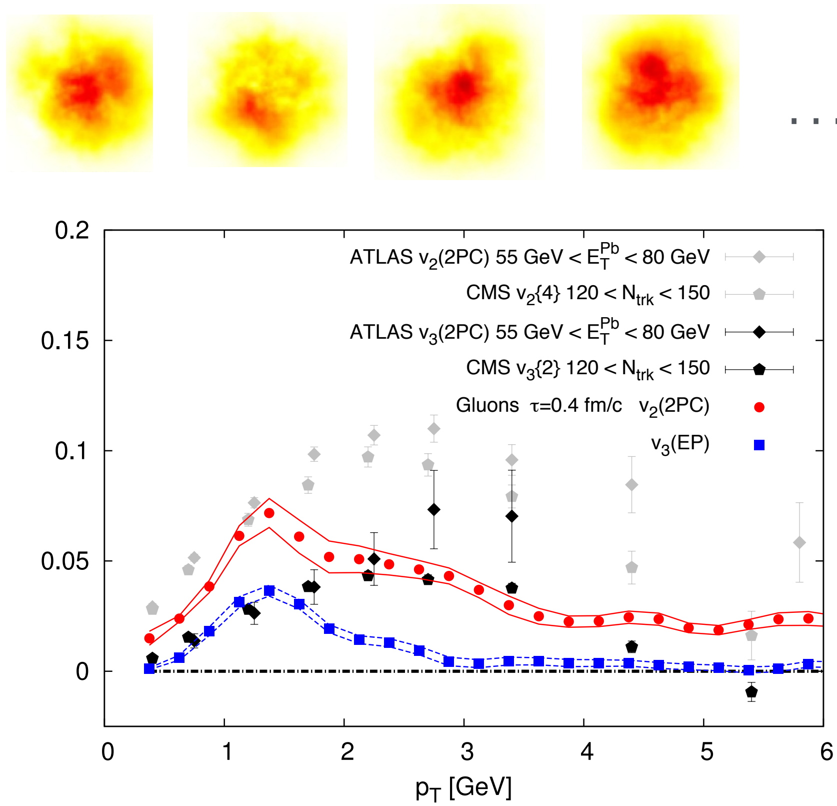



(SS, Schenke, Venugopalan arXiv:1502.01331)

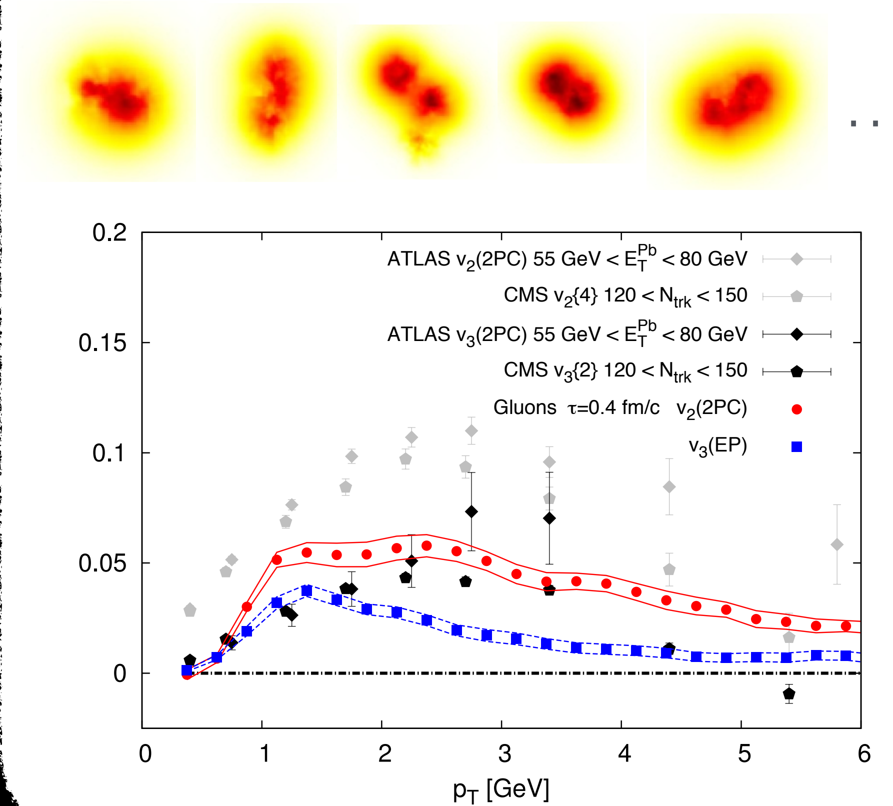
Comparison of event plane measurement vn{EP} and extraction from two particle correlation vn{2PC} yields compatible results

# Effect of event geometry

‘Spherical’ events




‘Eccentric’ events

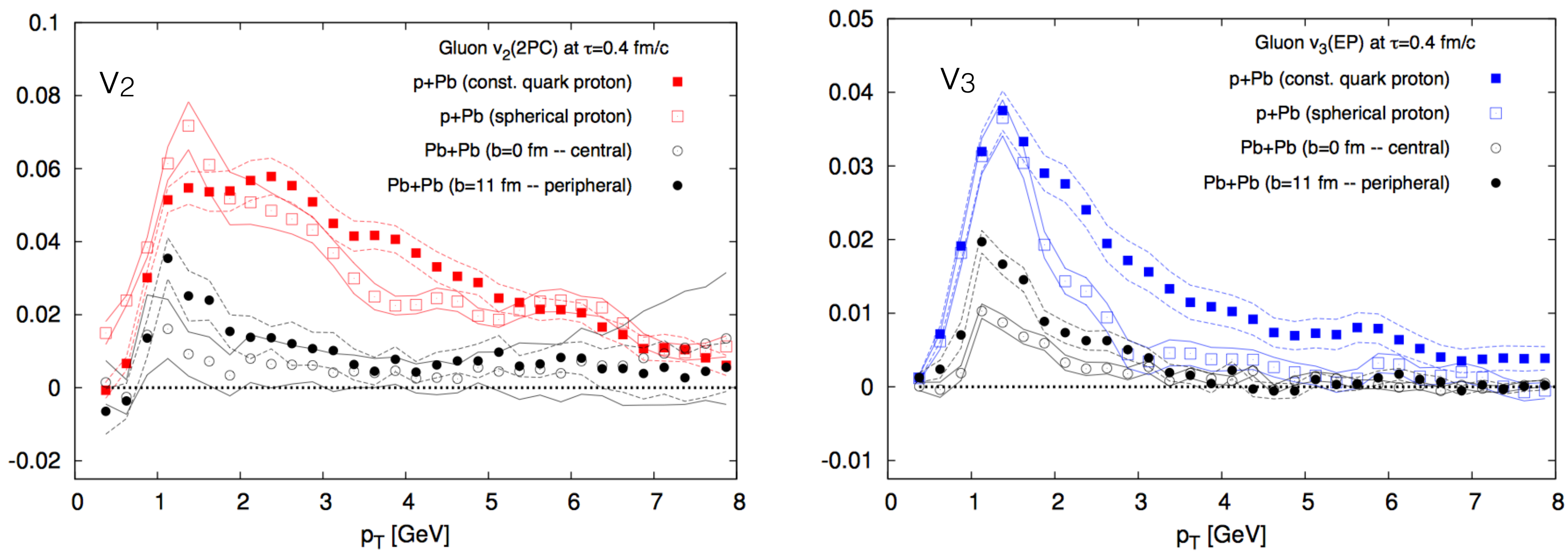



-> Small sensitivity to large scale structure
— very different from conventional hydrodynamic picture

-> No significant correlation between momentum space anisotropy vn and coordinate space anisotropy en

# System size dependence

Comparison of the effect in p+Pb and Pb+Pb




Significantly smaller effecting Pb+Pb -> points to importance of additional final state interactions to explain Pb+Pb data

Can be attributed to large number of mutually uncorrelated domains probed in Pb+Pb events

# Conclusions so far

- Initial state effects and early time dynamics ($\tau$<0.4 fm/c) can lead to sizable even ($v_{2,4,...}$) and odd harmonics ($v_{3,5,...}$) up to fairly large $p_T$.
- Correlations are rather insensitive to global event geometry and substantially larger effect in p+A as compared to A+A.

Still many open questions how to transition to final state

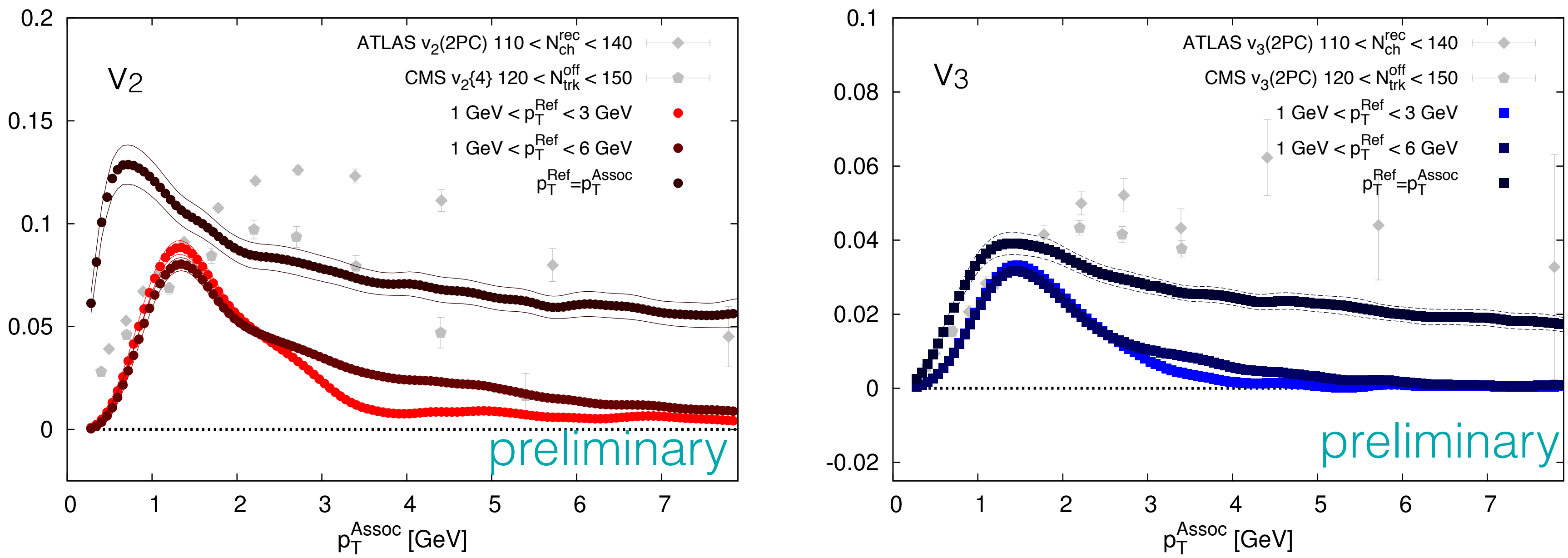
Hadronization? Measure correlations after fragmentation?
(work in progress matching CGC / PYTHIA)

Matching to parton cascade/onset of Hydrodynamic behavior?

Unless clear signs of final state interactions (e.g. jet quenching) can be observed experimentally, importance of final state effects needs to be addressed theoretically.

# More systematics at the gluon level

## Gluon $v_n$ in IP-Glasma model



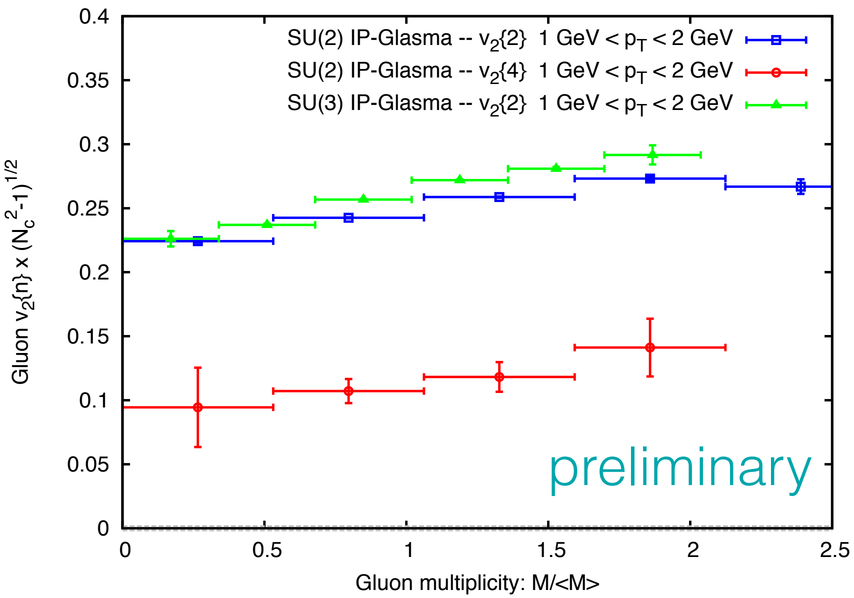

-> Significant anisotropies at high momenta however small correlation with low momentum particles

*Effect of Fragmentation?*

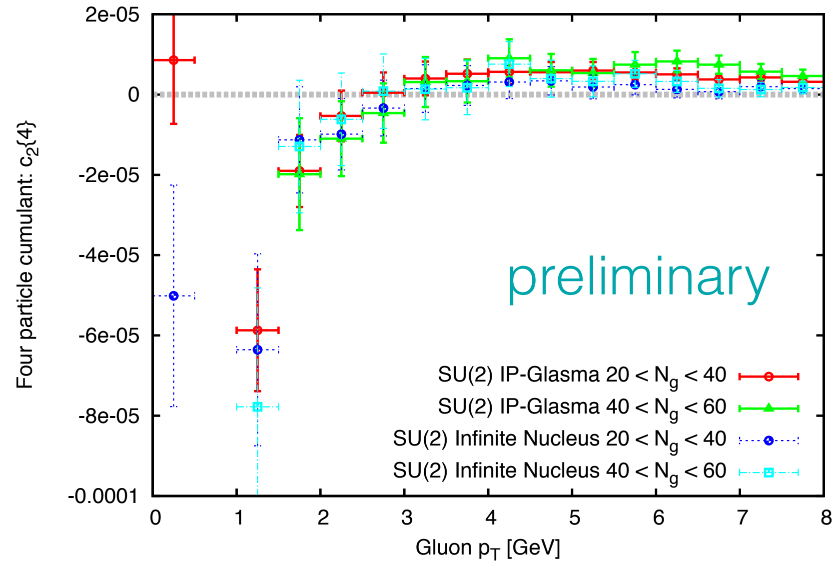
Schenke,Schlichting,Venugopalan work in progress

# More systematics at the gluon level

Multiplicity and $N_c$ dependence



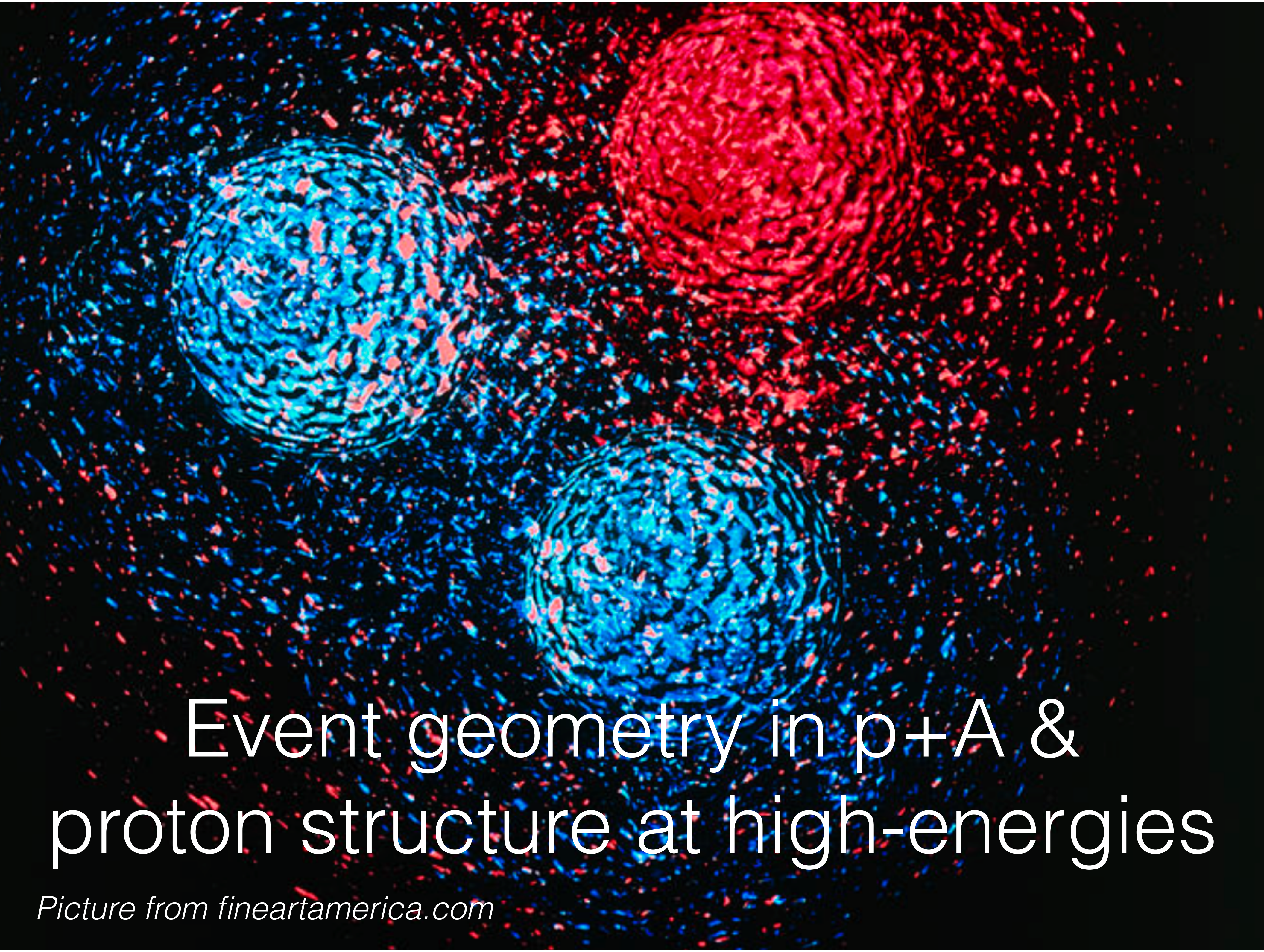

Higher cumulant $c_2\{4\}$
( measured in SU(2) )




- Correlation shows expected $N_c$ scaling
- Proof of principle of negative $c_2\{4\}$ at low momenta

Expect larger sensitivity of higher cumulants to detailed structure of gluon distributions — needs further investigation

Schenke,Schlichting,Venugopalan work in progress

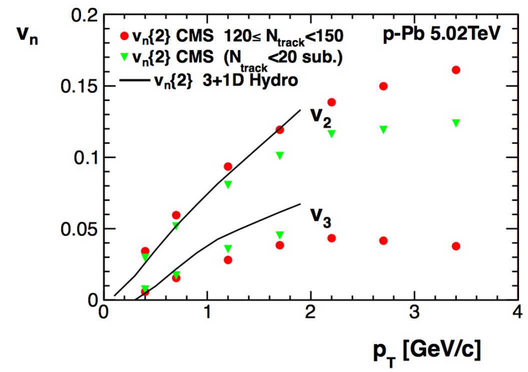


# Event geometry in p+A & proton structure at high-energies

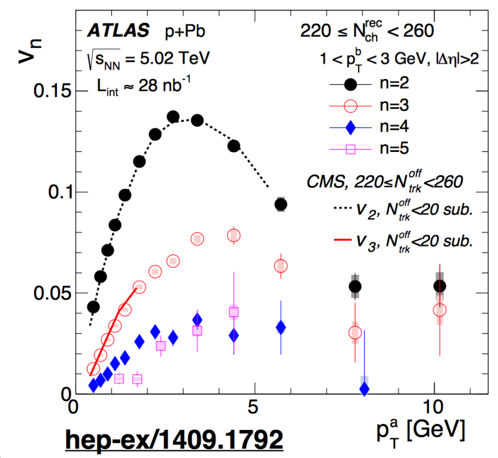
*Picture from fineartamerica.com*

# Hydrodynamics in p+A?

- *Azimuthal correlations due to creation of a small QGP with hydrodynamic expansion?* Some hydrodynamic calculations are able to reproduce experimental data.
- *But:* Viscous corrections more problematic for small systems due to larger gradients — validity of hydrodynamic framework in questions.
- No possibility to describe the high pT data — Hydrodynamics is an effective description for low energy degrees of freedom
- Strong sensitivity to initial state models!

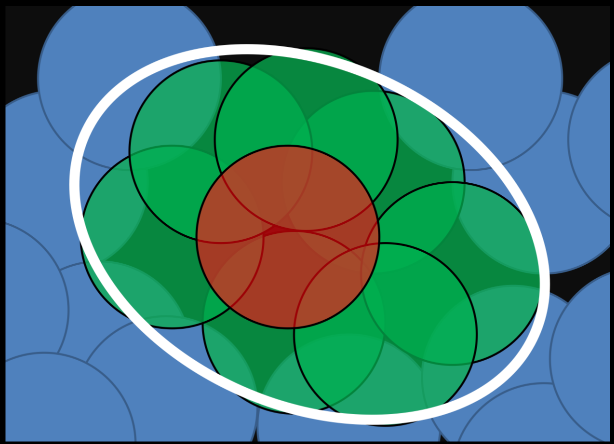



Bozek, Broniowski, Torrieri
PRL 111 (2013) 172303

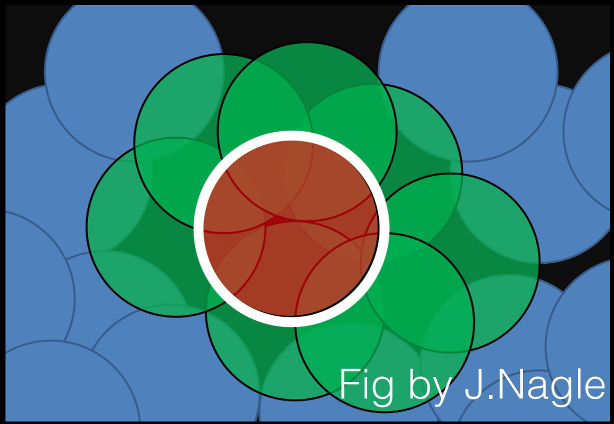



hep-ex/1409.1792

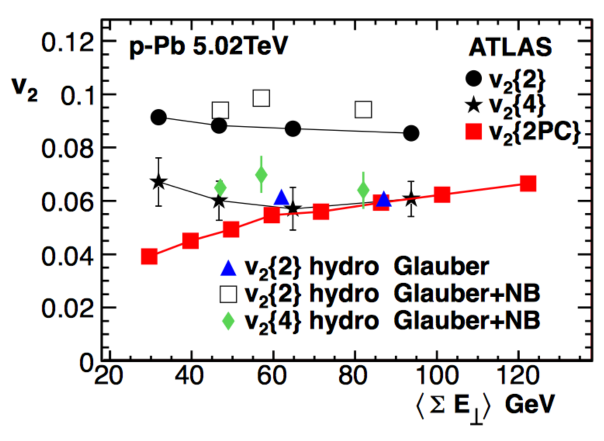
# Sensitivity to initial conditions

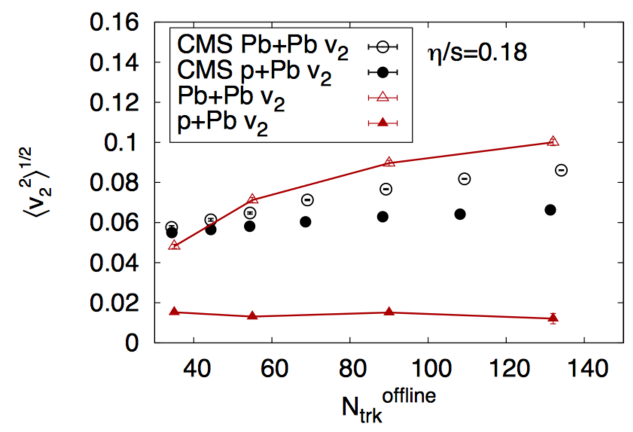


MC Glauber




IP Glasma

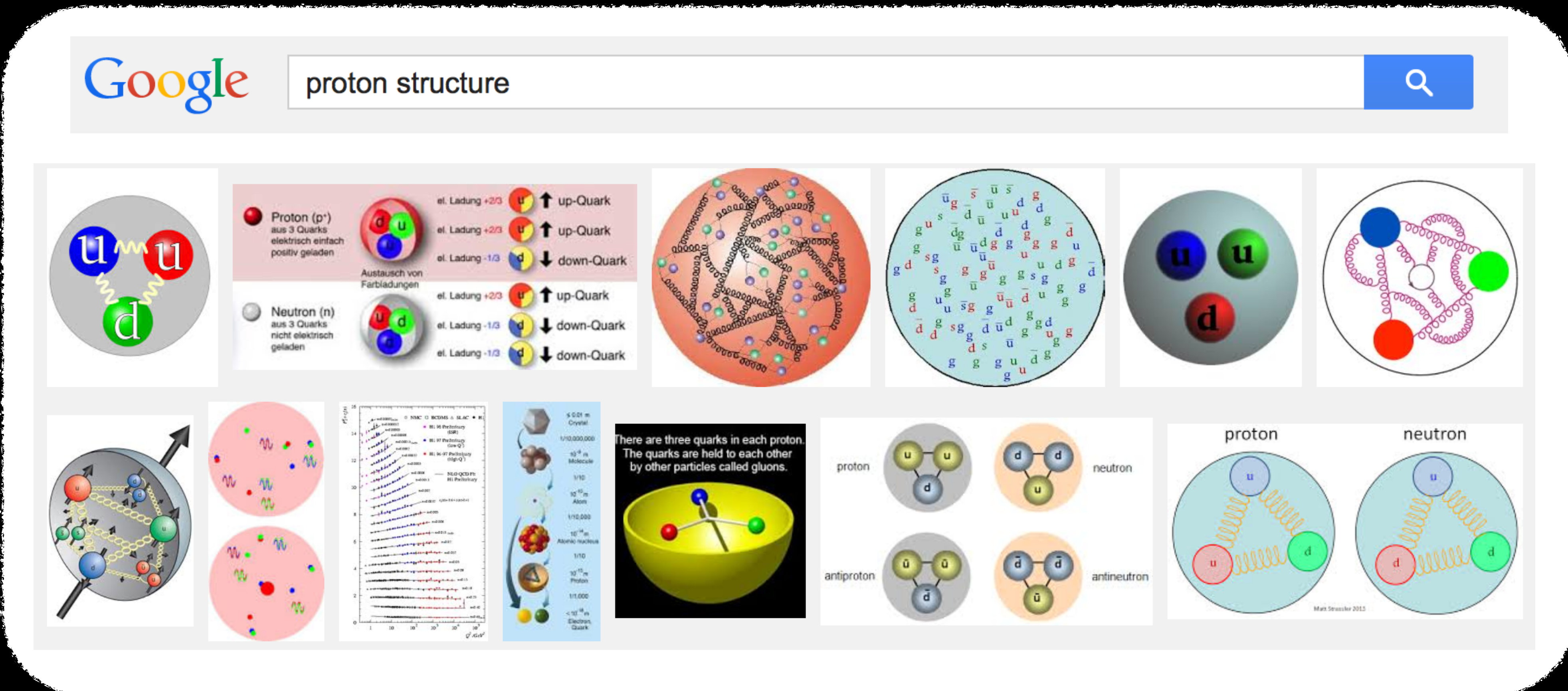



Bozek,Broniowski
PRC88 (2013) 1, 014903

Schenke,Venugopalan
PRL 113 (2014) 102301

# Origin of non-trivial geometry




- Valence structure at large x may well give rise to event-by-event fluctuations of the protons geometry

*What to expect for typical values of x probed in p+A collisions?*

# Small x evolution

Stochastic form of JIMWLK evolution equation
(Blaizot,Iancu,Weigert; Lappi,Mäntysaari)

$$V_{\mathbf{x}}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}}\mathbf{K}_{\mathbf{x}-\mathbf{z}}\cdot(V_{\mathbf{z}}\boldsymbol{\xi}_{\mathbf{z}}V_{\mathbf{z}}^{\dagger})\right\}V_{\mathbf{x}}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}}\mathbf{K}_{\mathbf{x}-\mathbf{z}}\cdot\boldsymbol{\xi}_{\mathbf{z}}\right\}$$

provides an efficient way to study small x evolution on an event-by-event basis.

Modification required to study impact parameter dependence
(Kovner, Wiedemann)

$$\mathbf{K}_{\mathbf{r}}^{(\mathrm{mod})} = m|\mathbf{r}|\ K_1(m|\mathbf{r}|)\ \mathbf{K}_{\mathbf{r}}$$

infrared regulator $m \sim \Lambda_{QCD}$ suppresses gluon radiation at large distance scales.

Slows down the growth of the proton radius to

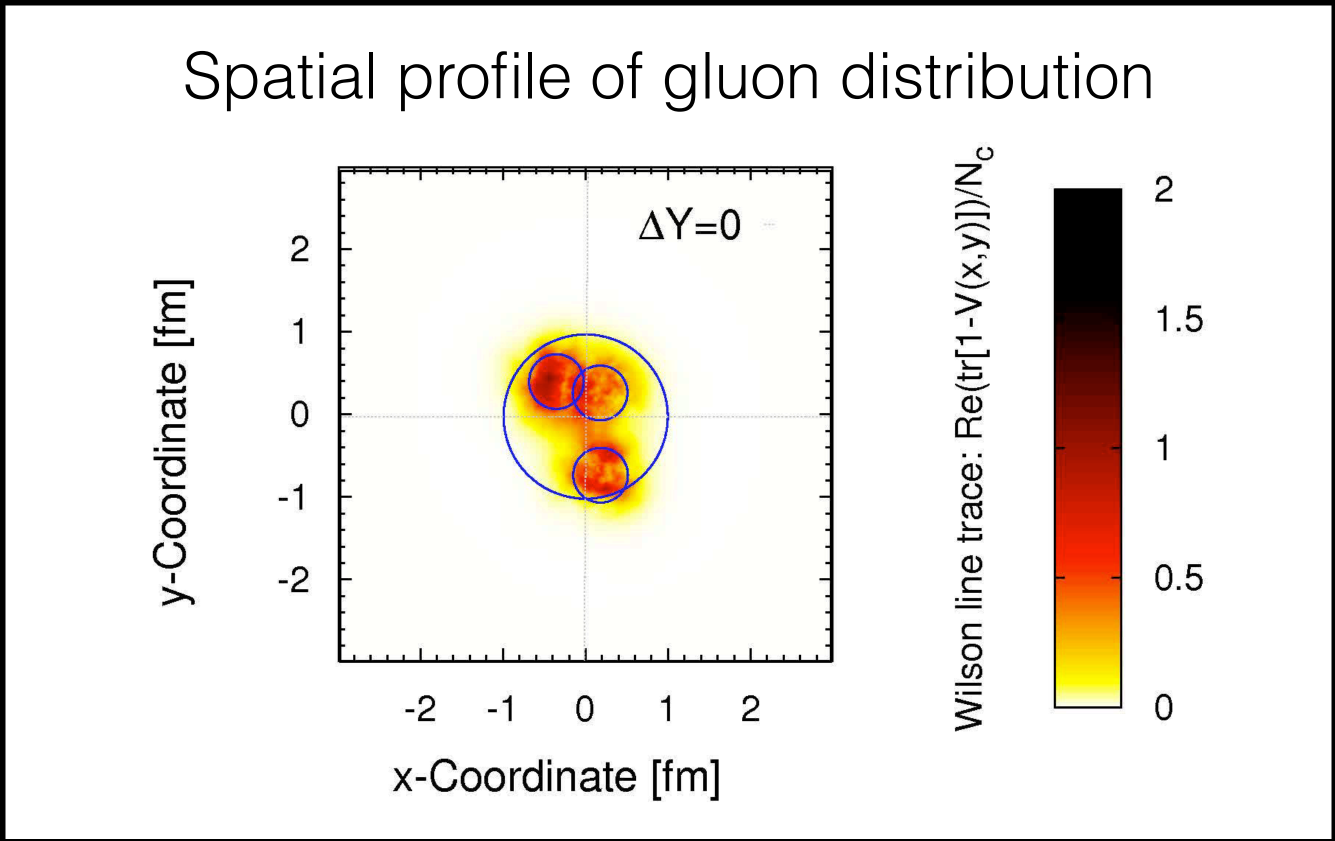
$$R_p \sim \alpha_s\ \Delta y/m$$

consistent with Froissart bound.

(SS, Schenke PLB 739 (2014) 313-319)

# Evolution of fluctuations

Consider fluctuating initial state at moderately small value of x
— inspired by constituent quark models

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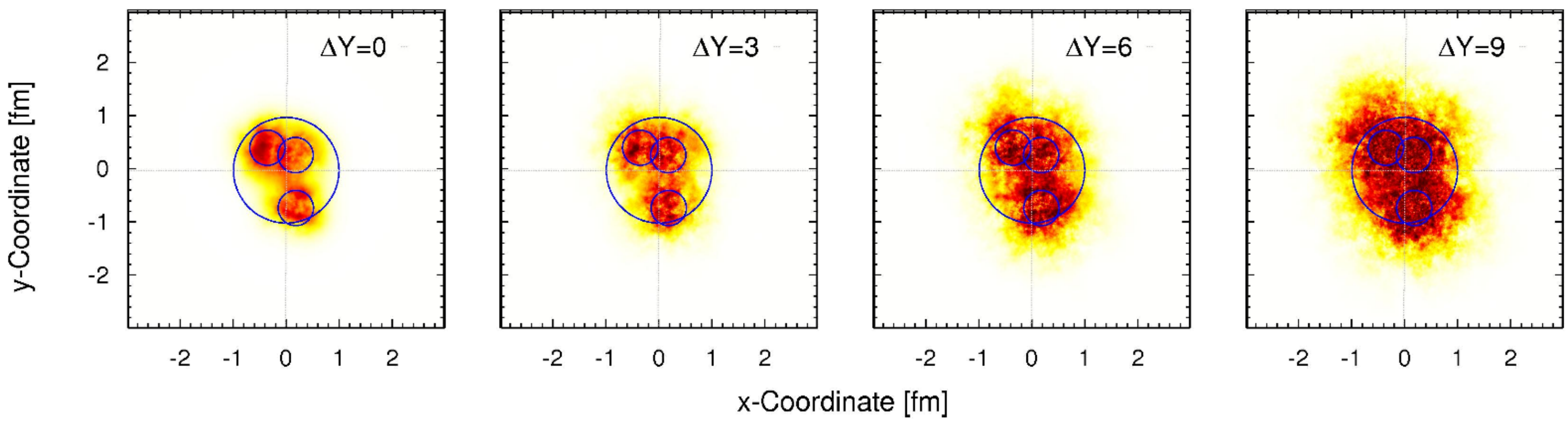
# Evolution of fluctuations




- Hadron radius increases linearly with rapidity — ‘Gribov diffusion’

-> Nucleon shape remains in tact even after evolution over several units of rapidity

- Small scale fluctuations develop and become finer and finer as characterized by the growth of $Q_s$ with rapidity

(SS, Schenke PLB 739 (2014) 313-319)

# Effect of proton structure on hydro results

- Hydrodynamic simulation of p+A collision with "ecc. protons"
  *(so far DIS constraints not taken into account for eccentric proton)*

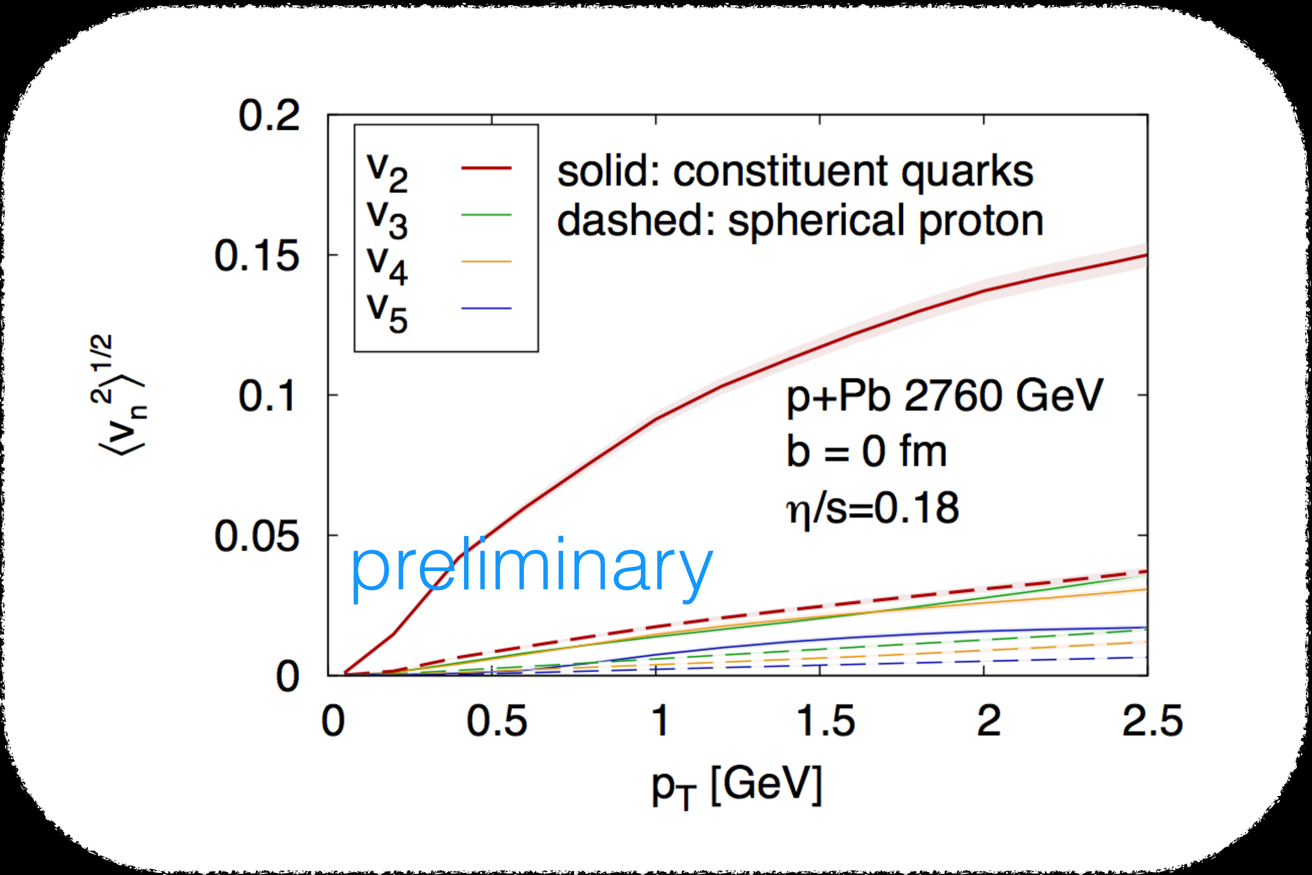



Fig. by B. Schenke

# Conclusions

- Event by event fluctuations appear on different length scales down to sub-nucleonic scales and play an important role in our understanding of p+A collisions at the LHC.

- Even large scale fluctuations ~$R_p$ are consistent with small-x evolution

  -> Importance to re-evaluate constraints on proton structure and event-by-event fluctuations from e+p

- Initial state and  early time effects lead to sizable correlations in small systems. Any theoretical calculation that does not take them into account is simply incomplete.

Still many open questions how to transition to final state

Ultimately understanding correlations in p+A really requires a better theoretical understanding of the early stages, possibly including equilibration dynamics and transition to hydrodynamics.